NASA TECHNOLOGY Facts

NASA Dryden Flight Research Center • P.O. Box 273 • Edwards, CA. 93523 • Voice 661-276-3449 • FAX 661-276-3566 • technology@dfrc.nasa.gov

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F-16XL Supersonic Laminar Flow

The porous titanium LFC glove is clearly seen on the left wing of test aircraft No. 2, the two-seat F-16XL. A suction system beneath the wing's surface was used to achieve laminar flow over 46 percent of the glove's surface while flying at a speed of Mach 2 in a successful demonstration of laminar flow at supersonic speeds.
NASA Photo EC96-43548-7

Laminar flow at supersonic speeds was successfully achieved in a two-phased NASA flight research program that used two delta-wing F-16XL aircraft from 1988 to 1996 to investigate active and passive laminar flow control (LFC) as a potential technology for a future High Speed Civil Transport (HSCT).

The goal of the LFC research program was to achieve laminar flow at supersonic speeds over 50 to 60 percent of the chord (from leading edge to the trailing edge) on the swept wing. The program ended with laminar flow demonstrated at a speed of Mach 2 over 46 percent of the wing's chord, slightly less than the original objective but considered extremely impressive to program researchers and engineers.

The F-16XLs were chosen for the LFC program because their cranked arrow (double delta) wings, maximum speed (Mach 2), and maximum operating altitude (55,000 ft) were similar to the wing design, cruise speed (Mach 2.4), and cruise altitude (60,000 ft) of the proposed HSCT. The cranked arrow configuration presents an inboard leading edge sweep of 70 degrees and an outboard leading edge sweep of 50 degrees.

Potential benefits of laminar flow over an aircraft's wings include increased range, improved fuel economy, and reduced aircraft weight. These benefits add up to improved economic conditions for those operating the aircraft, while also reducing the impact of exhaust emissions in the upper atmosphere where a supersonic transport would normally operate.

Other benefits stemming from a large high-speed transport incorporating laminar flow technology would be a reduced sonic boom signature at ground level due to weight reduction, and a reduction in airport takeoff noise levels. Aerodynamic heating due to skin friction would also be reduced with laminar flow, compared to increased skin friction created by turbulent boundary layers.

The two-phased LFC program commenced in 1988 with initial planning and development and continued until November 1996. All of the aircraft modifications and flights were carried out at the NASA Dryden Flight Research Center, Edwards AFB, Calif.

Phase 1 flights with XL No. 1 (single-seat aircraft) began in May 1990 and ended in September 1992 and studied the use of both active (suction) and passive gloves fitted on the left wing.

Initial Phase 2 flights with XL No. 2 (two-seat aircraft) studied a passive glove on the aircraft's right wing between January 1992 and July 1993. After a two-year modification period, an active glove made of extremely porous titanium was tested in Phase 2 between October 1995 and November 1996. It was during the 1995-96 flights that the 46% LFC measurements were charted.

Managing the LFC program was the NASA Langley Research Center, Hampton, Va. Team members were NASA Dryden, which handled all flight operations, Rockwell International, Boeing Commercial Airplane Group, and McDonnell Douglas Corporation.

What Is Laminar Flow?

As air flows over a wing, a thin layer of air normally clings to the wing surface. This thin layer of air is called the boundary layer, and it exists in one of two conditions: turbulent or laminar.

A turbulent boundary layer exists when the flowing air is bubbly, irregular, and when there are cross flow conditions. Wing surface irregularities also create turbulent conditions. All of these factors cause friction and drag. The frictional force between the wing and the air is called viscous drag, and overcoming this drag consumes a large percentage of the fuel needed to fly the airplane.

When the boundary layer is laminar (smooth) and without turbulence, irregularities, or cross flows, drag is reduced and less energy is needed to move the wing through the air.

Laminar conditions are hard to achieve and maintain. There are two basic techniques to achieve laminar conditions: passive (without mechanical devices), and active (using suction devices).

Passive laminar flow can be achieved in the wing design process, but the laminar condition is normally very small in relation to the wing's cord and is usually confined to the leading edge region. The North American P-51 Mustang fighter of World War II fame had a passive laminar flow wing, but laminar conditions existed for only a very short distance past the leading edge. Passive laminar flow can also be created on an existing wing by altering the cross-sectional contour of the lifting surface to change the pressure gradient. Both of these laminar conditions are called natural laminar flow.

Active LFC must be used to achieve laminar flow across larger distances from the leading edge. The main means of achieving active LFC is to remove a portion of the turbulent boundary layer with a suction mechanism that uses porous material, slots in the wing, or tiny perforations in the wing skin.

The F-16XL aircraft used in the LFC study were modified to operate a suction system that pulled the turbulent boundary layer through a porous sheet of titanium that was the upper wing surface in the test area.

Research has shown that a suction system is the only efficient method that can reduce the sweep-induced cross flow disturbances associated with turbulent boundary layers on swept-wing aircraft.

Ludwig Prandtl, a German scientist, discovered the existence of a boundary layer between a fluid (air) and a solid body (wing) in 1904. His studies of fluid mechanics and aerodynamics helped advance wing designs in the infant days of aviation.

Laminar Flow Research of the Past

The first known research into laminar flow control began in 1939 at the NACA (National Advisory Committee for Aeronautics) facility that is now the NASA Langley Research Center, Hampton, VA. Engineers there tested a suction device that incorporated slots in the wings of wind tunnel models. NACA engineers using a B-18 twin-engine aircraft to flight-test an LFC test panel on the aircraft's left wing followed up these studies in 1941. The results were favorable.

NACA curtailed LFC studies during World War II, but British scientists continued with passive LFC research on several modified military aircraft while German and Swiss engineers investigated active control on wind tunnel models.

Research by NACA following World War II resumed in 1946 with wind tunnel studies of a suction system using a porous airfoil skin made of low-strength bronze. Tests results reported that laminar conditions were attained over the full-chord distance. The metal's low strength and weight, however, made the design impractical for general use at that time.

Through the 1940s and 1950s, research on suction designs continued in the U.S. at NACA's Langley facility, and also by Northrop Aircraft. In Europe, the British Royal Aircraft Establishment (RAE) and also Handley Page led British efforts. Some success was reported on both sides of the Atlantic Ocean, but in most cases laminar flow was limited to short chord distances because of tiny surface disturbances and irregularities.

In 1953, RAE researchers tested a rolled metallic cloth on the wing surface of a Vampire aircraft, but roughness within the mesh contributed to excessive turbulence.

Much of the work in the 1950s and 1960s, especially by Northrop and the British, centered on investigating various suction hole and slot arrangements, sizes, spacing, and orientation in sheet metal used for wing surfaces. Studies also continued on the use of porous materials.

In a program sponsored by the U.S. Air Force in the 1950s, Northrop achieved full-chord laminar flow over an active wing glove mounted on an F-94 aircraft while flying at subsonic speed. However, full-chord laminar flow disappeared when the aircraft was flown to higher speeds.

A later program by Northrop, also sponsored by the U.S. Air Force, used two RB-66 aircraft to study active LFC on slotted wings that were moderately swept. The two aircraft were redesignated X-21A and X-21B and were used to research numerous areas of concern including insect contamination on suction systems, the significance of atmospheric ice crystals upon laminar flow, surface smoothness, and spanwise turbulence. By the end of the X-21 program in the mid-1960s, laminar flow been achieved over 95 percent of the wing's experimental area.

NASA's interest in laminar flow rose in the 1970s with increased concern over petroleum prices and fuel efficiency and triggered a project using an F-111. The joint Dryden-Langley project added passive natural laminar gloves with supercritical airfoils to the aircraft's variable sweep wings in the late 1970s and flight-tested them through a range of sweep angles. The aircraft was designated the F-111 TACT (Transonic Aircraft Technology) demonstrator and several years earlier was used to test supercritical airfoils on variable sweep wings in program involving NASA and the Air Force.

Data from the F-111 TACT flights helped to plan similar research between 1984 and 1987 using an F-14 to study natural laminar flow at even greater wing sweep angles.

Both of these flight projects produced significant data relating to the degree of wing sweep at subsonic flight before natural laminar flow is lost.

Meanwhile, in 1982, NASA teamed with Douglas and Lockheed engineers to develop individual wing leading edges on a JetStar business transport. The overall project, called the Leading Edge Flight Test (LEFT) investigated three areas that could be factors in LFCs on large passengers jets: suction systems, protection against insects clogging suction systems, and de-icing.

Lockheed's LFC system, with ducts incorporated into the wing structure, had 27 spanwise slots in the upper and lower wing surfaces. Pressurized fluid forced through slots on the leading edge was used to prevent the accumulation of ice and insects.

The Douglas LFC configuration used less ducting and featured perforated suction strips. A retractable flap covering the wing's leading edge was a barrier to insects, while small spray nozzles installed on the inside of the flap prevented the buildup of ice.

Flights to investigate each system began in November 1983 and continued until October 1987. During this lengthy period, NASA flew many simulated airline flights to compare the two systems in conditions of rain, snow, icing, heat, and tropical conditions. When the project concluded, the Douglas wing had achieved 95 percent laminar flow and the Lockheed device registered between 80 and 94 percent laminar flow. But on the negative side, clouds and ice contributed to the disruption of laminar flow until the aircraft was back in good weather conditions. Also, researchers said, the weight of the mechanisms needed for good active LFC was too great for efficient operations.

In 1990, before the F-16XL LFC flight tests commenced, NASA Langley teamed with the Air Force and Boeing to test a hybrid LFC wing glove on a commercial 757. The glove was similar to the leading edge flap unit tested on the JetStar. Along with the flap, the 757 glove incorporated a perforated titanium suction section and was engineered with the capability of reversing airflow to purge the pores of contaminants. Researchers reported the flight tests were successful and encouraging.

The F-16XL Laminar Flow Flight Program

The LFC program using the two F-16XL aircraft was a two-phase effort using each aircraft to explore both active and passive LFC wing gloves at subsonic and supersonic speeds.

Both aircraft were instrumented with a flight test nose boom to record total and static pressure, and angles of attack and sideslip. Other measurements recorded during each research flight were total and static temperatures, accelerations, and the positions of each control surface. Besides these measurements, each passive and active glove was instrumented to record many parameters during each flight.

F-16XL-1

Aircraft No. 1 was used in Phase 1 operations. The wing glove, designed and fabricated by Rockwell International, was delivered to NASA Dryden in July 1989 for instrumentation and installation. The glove, installed on the aircraft's left wing, was a large passive area incorporating all of the inboard leading edge and about 50 percent of the cord. The smaller active glove section, covering less than half of the inboard 70-degree leading edge, used a titanium skin perforated with many thousands of tiny holes. The ducted suction system that pulled the turbulent boundary through the perforated skin was powered by an air conditioning turbocompressor from a Convair 990 that operated off of bleed air from the XL's engine. The suction unit was mounted inside the aircraft's ammunition drum bay.

Instrumentation installed on the active-passive glove included over 80 flush static pressure orifices, 30 hot-film sensors at locations that varied with each flight, and three skin temperature gauges.

There were 31 flights in the initial Phase 1 operation and they demonstrated that large regions of laminar flow could be obtained with an active glove on a highly swept wing at supersonic speeds. The flights commenced in May 1990 and concluded in September 1992.

The data were obtained for a Mach range of 1.2 to 1.7 and an altitude range of 35,000 to 55,000 feet. Laminar flow, however, was not achieved with the active glove at the exact design point of Mach 1.6 at 44,000 feet.

F-16XL-2

Armed with successful supersonic laminar flow data from flights with aircraft No.1, LFC program personnel moved ahead with Phase 2 to gain even more information about laminar flow behavior at various supersonic speeds.

Phase 2 was carried out in two parts. The first part was installation of a passive glove on the right wing of aircraft No. 2 to basically study detailed surface pressure distribution along the wing's leading edge. The glove, crafted of foam and fiberglass, covered the entire inboard 70-degree leading edge, but very little of the wing cord. The speeds of the tests ranged from Mach 1.4 to 2.0 at an altitude range of 45,000 to 50,000 feet and were carried out between January 1992 and July 1993.

The second and final round of LFC flights with aircraft No. 2 began in October 1995 following a two-year period to install the active titanium glove on the aircraft's left wing. The titanium panel, fabricated by Boeing, was 0.040-inches thick and perforated with more than 12 million laser-drilled holes. It extended 17 feet down the wing's inboard 70-degree leading edge and covered 60 percent of the cord. Part of the external modification project was installation of a leading edge extension to continue the 70-degree inboard sweep straight into the fuselage. The titanium suction panel was blended into the existing wing contour with a carbon-fiber fairing.

The suction panel beneath the titanium skin was divided into regions or chambers. A system of flutes and valves controlled the rate of air drawn through the titanium skin panel in each region. Suction was provided by a modified Boeing 707 cabin-air pressurization turbocompressor mounted in the ammunition drum bay.

Instrumentation on the glove included pressure orifices, thermocouples, microphones, mass flow sensors, and hot-film anemometers. All instrumentation data were transmitted in real time to the control room during each flight, and also recorded for later analysis.

The aircraft was flown 45 times with the LFC modifications, beginning in October 1995 and continuing into November 1996.

Before flights commenced concern arose that the engine inlet configuration would generate a shock wave that could impact the leading edge of the glove and affect laminar flow conditions in that region. To prevent this, a 20-inch aluminum vertical shock fence was mounted on a weapons attach point on the lower surface of the wing butt. Two fence designs were flown on 43 of the 45 research flights: 19 flights with the front of the fence raked rearward at 60 degrees and 24 flights with a fence raked rearward at 10 degrees. Two flights were made without the fence to obtain baseline data.

Flight data showed that even with shock fences installed to protect the leading edge of the active glove, it was necessary to fly the aircraft at an angle of sideslip of 1.5-degrees nose right. A small shock wave generated by a canopy joint also created slight pressure disturbances on the glove's upper surface. These irregularities, however, would not be present on a future aircraft using active LFC technology.

Flight Results and Benefits

Data produced during the LFC flight research program demonstrated laminar flow over 46 percent of the wing chord while flying at a speed of Mach 2 at altitudes of between 53,000 and 55,000 feet. This does not match the pre-flight design points of 50 to 60-percent chord coverage at Mach 1.9 and an altitude of 50,000 feet, but program officials considered the program to be very successful.

Designing, installing, and flight testing the active laminar flow glove was a technological challenge carried out in a program that was considered a national priority and it had self-imposed deadlines. These factors brought the industry-NASA team together in an effort that is a model of cooperation, efficiency, and productivity.

The goal of the LFC program was to provide data for a specific application -- a proposed civilian high-speed passenger transport capable of flying at supersonic speeds. The proposed transport has yet to be developed, but the information generated by the NASA LFC program can be extremely useful to engineers considering future aircraft designs that may incorporate laminar flow technology as a way of flying more efficiently on less fuel.